

CASE FILE COPY

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2322

CREEP OF LEAD AT VARIOUS TEMPERATURES

By Peter W. Neurath and J. S. Koehler

Carnegie Institute of Technology



Washington
March 1951

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2322

CREEP OF LEAD AT VARIOUS TEMPERATURES

By Peter W. Neurath and J. S. Koehler

SUMMARY

A creep apparatus capable of measuring the stress-strain-time relation in the strain range 10^{-4} to 10^{-2} inch per inch with some accuracy (smallest readings are about 2×10^{-6} in./in.) and at temperatures down to that of liquid nitrogen was constructed. Before completion of this apparatus, data at room temperature were obtained with a preliminary model.

Single crystals of lead were grown, some for the preliminary tests and some of a special shape for the final apparatus, and these were oriented by X-ray analyses. In addition, some copper and two zinc crystals were also grown and tested.

The tables and curves of the results of these creep tests indicate that

(1) A very slight change, if any, of the yield point of lead crystals occurs between -190° and 30° C. (The yield point has been taken as that given by the resolved shear stress necessary to produce a strain of 10^{-3} in./in. within a few hundred minutes.)

(2) A radical change of the shape of the stress-strain-time curves occurs with decrease in temperature.

(3) The stress-strain-time curves for copper at room temperature are very similar in shape to those for lead at -190° C, yet they cannot be made to coincide with the lead curves by changing the temperature at which the experiment is performed. The copper crystals will presumably always be several times as strong, even compared with lead crystals at very low temperatures.

(4) Some work-hardening of lead takes place at room temperature and is only partially removed by annealing at room temperature even for periods of several weeks.

(5) Working of the crystal influences creep rates more easily and more permanently than it does the yield point.

(6) Zinc is appreciably weaker than lead at room temperature. The effect of orientation is noticeable, and the calculation of resolved shear stress brings the yield-point values into fair agreement.

INTRODUCTION

The present investigation was undertaken to secure stress-strain curves, creep data, and elastic constants for single crystals of lead over a wide range of temperatures. The investigation was conducted at the Carnegie Institute of Technology under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics in association with theoretical work performed at the Lewis Flight Propulsion Laboratory. The work on copper and zinc was supported by the Office of Naval Research.

The authors would like to thank Mr. John Marx and Mr. J. B. Wachtman, Jr., who have unselfishly given much of their time, and Mr. T. Blewitt and Mr. J. Pittenger, who, apart from other aid, did some of the earlier work on this project.

DESCRIPTION OF CREEP APPARATUS

The creep apparatus is constructed around a conventionally shaped tensile specimen, to which two Tuckerman strain gages are applied. (See fig. 1.) These are optical strain gages, manufactured by the American Instrument Co., in which the extension or compression of the specimen rotates a stainless-steel mirror. Light made parallel by the autocollimator is reflected from the mirror and hence deflected by its rotation. A scale in the autocollimator enables one to read the extension directly by observing the movement of the reflected image. The mirror-prism arrangement gives rise to two images, called the compression and tension image, respectively, which move in opposite directions when the specimen undergoes some fixed strain. Only one of them appears in the field of view of the autocollimator at one time. The operation is as follows: The compression image is set at about 25 divisions, that is, at full scale, which is equal to a strain of 50×10^{-4} inch per inch for the two gages; one division on one gage corresponds to 2×10^{-4} inch per inch. Thus the average strain of the specimen, in 10^{-4} inch per inch, is numerically just the sum of the two gage readings. Extension of the specimen moves the compression image to zero; 10 divisions later (during 2 of which neither image can be seen in the field of view at all) the

tension image has appeared and come up to 0. It can then be followed to 25, giving a total possible strain measurement without adjustment of the gages of 1.2 percent. This is the range in which the measurements have been made. The vernier divisions on the image (see fig. 2) allow readings to be made to 1/50 division, with imagination to 1/100, making detectable average strains of 4×10^{-6} or 2×10^{-6} inch per inch, respectively.

The specimen and strain gages, which are held against it by flat springs mounted in special supports (see fig. 3) (note that their weight is held chiefly by the specimen), must be mounted so that the temperature of the specimen can be altered at will. For this purpose they have been enclosed in a double-walled stainless-steel cryostat (see fig. 4). With the help of a prism system remote reading of the gages is possible, and the whole assembly, including the loading mechanism, can be evacuated. By this means it is possible to control the cooling rate of the specimen when, for example, the cryostat is surrounded by a Dewar vessel containing liquid nitrogen. Also, and this is of major importance, the vacuum makes it possible to prevent the fogging of the optical parts inside the cryostat. The double-walled cryostat is soldered to the lid for each run by means of Wood's metal.

The loading device (see fig. 5) is simply a sliding weight operated by a 1-rpm motor through reduction gears. Different weights for use with different metal samples (a heavier one for copper, a lighter one for lead and zinc) are provided. The whole loading assembly is in vacuum; its vacuum chamber is connected to the vacuum system of the cryostat, so as to avoid the friction and influence of pressure differences inherent in vacuum seals.

The cryostat may be surrounded by a large stainless-steel Dewar vessel of almost 12 gallons' capacity. This can then be filled with liquid nitrogen, or for higher temperatures with heat-transfer oil. For the latter case a micro-set thermo-regulator, electric heating coils, water-carrying cooling coils, and a circulating pump of large capacity are provided. The cooling coils are necessary to compensate for the considerable heat input of the pump. The heating coil is the element controlled by the relay operated by the thermostat.

The loading rod and the grip (see fig. 6) with the knife edges and flexible joints are designed to minimize bending and for ease of inserting a specimen. To the grips are soldered two thermocouples with which the temperature changes at the top and at the bottom of the specimen may be measured with considerable accuracy, in fact, with more accuracy than is probably necessary. Scaffolding and cranks for lifting the Dewar vessel and the case of the loading device are provided. (See fig. 7.) Without them considerable jarring of the device is unavoidable. This jarring

is sufficient to destroy the adjustment of the sensitive strain gages and it is possible that it might cold-work the specimen.

It should be noted that the setting of the strain gages so that the image is on scale requires some skillful manipulation and cannot be done without slightly pressing and scraping against the specimen. For soft specimens, such as lead or zinc, this is a disadvantage. However, it is hoped that the practice gained in operation made this a small factor.

PREPARATION OF SPECIMENS

All crystals run before July 1948, when the new creep apparatus finally went into operation, were cut from long cylindrical rods about 5 millimeters in diameter. These crystals were grown by the Bridgman method. They were vacuum-cast at a pressure of about 10^{-5} millimeters or lower, the crucible and metal being thoroughly outgassed in the process. Analyses, as far as available, are given in table I. For the copper, the crucibles were made of graphite, and the casting and growing, done by lowering these through the furnace, were done in a continuous process in a furnace developed for this work. The invaluable aid of Mr. T. Blewitt in connection with this is gratefully acknowledged here. The lead and zinc were cast in Pyrex tubing lubricated with aquadag. These tubings were sealed off and then lowered through the growing furnace. The outgassing and casting for the lead and zinc were always done about 50° C higher than the growing. Two-inch lengths were then cut from these cylinders, some of which were single crystals about 6 or 8 inches long. These 2-inch lengths were soldered with Wood's metal to brass cylinders with holes for pins in them (see fig. 8), which in turn could be placed into the holders of the old loading device. A special mounting jig was used to facilitate this operation, but the practice was finally abandoned in favor of using crystals with integral ends for gripping.

All the new-type crystals, distinguished in the numbering by a prefix N, have been cast in graphite in special crucibles (see fig. 9). This provides pairs of crystals of the same orientation and of presumably identical composition. The crystals are cut off to the right length with a jeweller's saw while still in the crucible. They are removed from the crucible by milling grooves 120° apart into the graphite cylinder almost down to the metal. Two of the graphite segments can then be broken off easily and the specimen lifted from the third. After removal they are cleaned and etched chemically to see whether they are single crystals. For lead, two parts of acetic acid and one of hydrogen peroxide are used for a polish. This also acts as a fair macroetch. For greater contrast a specific macroetch (3 parts acetic acid, 4 parts nitric acid, and

16 parts water) is used. Corresponding standard etches and polishes are used on copper and zinc. The flux used to solder the old-type specimens into the holders proved detrimental to the polish.

Laue pictures of the specimens were made. The lead oxide is removed with pure acetic acid. This is washed off thoroughly with distilled water and an exposure started as soon as the lining-up process allows. With the X-ray equipment a 6-hour exposure then usually gives a sufficiently strong pattern so that an orientation of the specimen can be made. It should be noted that some of the Laue patterns show double spots. This is indicated in the summarized table (table II) for the crystals. From the orientation and the diameter of the crystals the resolved shear stress τ_r along the active slip direction may be calculated by the following formula:

$$\tau_r = \frac{4P}{\pi d^2} \cos \phi \cos \lambda$$

where

P load, kilograms

d diameter of specimen, millimeters

ϕ angle between specimen axis and normal to most probable slip plane, degrees

λ angle between specimen axis and most probable slip direction, degrees

It should be noted that for face-centered-cubic crystals $\cos \phi \cos \lambda$ varies only within about ± 10 percent. Thus any effect due to orientation will quite likely be small. Changes in diameter d being squared have a larger influence on τ_r . The value of d is not simply the 3/16 inch of the quite accurately made crucibles, because of the etching process.

Finally it should be emphasized that these pure single crystals are very soft and that extreme care must be exercised in handling them to prevent severe bending. Many crystals never get so far as a creep test.

TEST RESULTS

The test data and various quantities calculated from them are presented in summarized form in table II. In addition complete curves are given for several specimens which are considered representative.

(See figs. 10 to 16.) The plots have been done in terms of strain against time, and consist of different portions, each one of which was obtained with a definite stress; the stresses generally increase in going from one step to the next. The shape of the stress-strain-time curves changed radically with decrease in temperature. Two types of curves were obtained schematically, as shown in figure 17.

Figure 17(a) shows what is termed "transient creep," although it is possible that the small creep rates of the leveled-off portion would remain finite indefinitely. Note however that in cases where a long period of time was allowed to elapse the total extension observed always remained very small, quantitatively speaking less than one-tenth that of the instantaneous step, in as long a time as 500 minutes.

Figure 17(b) is similar to figure 17(a) up to some resolved shear stress which, in these experiments, might be called the critical shear stress, and is also the stress at which the strain exceeds 10^{-3} . Beyond that, curves of the type in figure 17(b) show much less transient creep than curves of the type in figure 17(a), but show considerable "steady-state" creep. However, possibly because of outside disturbances such as vibrations and handling on loading and adjusting (avoided to a considerable extent in the creep apparatus now in use), this creep is steady only in the sense that the rate does not decrease at zero. There is some indication that at a given temperature and stress this rate has a maximum which it only reaches some time after loading to that stress because the loading itself with its accompanying transient creep "work-hardens" the specimen temporarily.

From curves of the type in figure 17(a), which apply to copper at room temperature and to lead at -190°C , it is possible to read or calculate

- (1) The critical resolved shear stress $\tau_{r,cr}$.
- (2) The ratio of increment of strain to increment of stress $\Delta\epsilon/\Delta\tau_r$ for each step. This does not seem to increase greatly with τ_r in the region investigated.
- (3) Steady-state creep rates $\Delta\epsilon/t$ (ratio of increment of strain to increment of time) between such points as A and B. Not too much reliance should be placed on these rates. They may be evidence of small discontinuous steps induced by vibrations rather than of any quasi-continuous creep.

From curves of the type in figure 17(b) it is generally not possible to calculate item (2) as the transient steps are largely hidden by the large steady creep rates. So only items (1) and (3), the latter now being unmistakably measurable, are obtained. Where the creep rate changes

without any apparent change in the load, various values are given in the order of their occurrence. It should be noted that these creep rates rise very rapidly with a small increase in load.

An attempt has been made to list all relevant data in table II. However, reference to the curves (figs. 10 to 16) should be made to appreciate the significance of the tabulated values. Creep rates for crystals run more than once show that for lead at room temperature a certain amount of work-hardening is possible, and it persists over long periods of time (note lead specimen 2c). This work-hardening is only partially removed by annealing at room temperature even for periods of several weeks. Working of the crystal influences creep rates more easily and more permanently than it does the yield point. The yield point has been taken as that given by the resolved shear stress necessary to produce a strain of 10^{-3} inch per inch within a few hundred minutes. A very slight change, if any, of the yield point of lead crystals occurs between -190° and 30° C.

The stress-strain-time curves for copper at room temperature are very similar in shape to those for lead at -190° C, yet they cannot be made to coincide with the lead curves by changing the temperature at which the experiment is performed. The copper crystals will presumably always be several times as strong, even compared with lead crystals at very low temperatures. The few zinc data indicate that zinc is appreciably weaker than lead at room temperature. The effect of orientation is noticeable, and the calculation of the resolved shear stress brings the yield-point values into fair agreement.

Another feature that may be noted takes place under conditions in which transient creep is observed. When the apparatus is disturbed some time after an application of stress has given rise to a strain transient, a second transient, generally smaller, appears. The sum of these two $\Delta\epsilon$'s gives the higher value of $\Delta\epsilon/\Delta\tau_r$ where two are given for one stress $\tau_{r,1}$. Now it is apparent that when this process takes place the value of $\Delta\epsilon/\Delta\tau_r$ for the next higher value of stress $\tau_{r,2}$ is lower, and by such an amount that the average of the two successive values of $\Delta\epsilon/\Delta\tau_r$ comes to about the average of all the values of $\Delta\epsilon/\Delta\tau_r$ for the run in question. See lead specimen N3b where τ_r is 118 and 124 grams per square millimeter, or lead specimen N4b where τ_r is 117 and 123 grams per square millimeter (table II). The obvious conclusion is that the vibration has temporarily increased the value of τ_r over the nominal amount. As unloading produces only a very slight, mostly elastic, contraction, which is negligible compared with a strain of 10^{-3} inch per inch, there is no more direct evidence of this temporary increase in load in the curves. Unloading by about 142 grams per square millimeter results in a strain of only -3.4×10^{-4} inch per inch, compared with an

extension of about 140×10^{-4} inch per inch on loading. Under transient-creep conditions it appears that unloading the sample and then reloading it to the same load produces only a very slight net strain of the order of 10^{-5} inch per inch. Hence no time has been spent thus far on an investigation of this phenomenon.

CONCLUDING REMARKS

In conclusion, some of the difficulties encountered in making the measurements should be pointed out. Bending will produce spurious results particularly when very small strain measurements are made. The two strain gages used simultaneously agree to within about 25 percent over the 1-percent range, but in the initial one-hundredth or one-thirtieth of that range the differences are often much larger. Another problem is that of vibration and/or shock. This prevents the accurate measurement of creep rates of less than 10^{-6} inch per inch per minute, or at least makes them suspect.

Judging from the results obtained so far it would be interesting to get further data

- (1) On lead at 100° C
- (2) On copper at -190° C
- (3) On other metals, such as zinc, aluminum, and magnesium, both face centered cubic and hexagonal, at various temperatures

As all these measurements would be made on very pure materials under identical experimental conditions they should enable one to make significant comparisons between these metals. The few scattered creep data available so far were obtained under a variety of conditions and do not allow significant comparisons to be made.

Carnegie Institute of Technology
Pittsburgh, Pa., September 7, 1949

TABLE I

ANALYSES OF LEAD SAMPLES

[Performed by Research Department of American Smelting and Refining Co.]

Lead sample	Impurity	Percentage of impurity
^a 60	Bi	0.001
	Cu	.0002
	Sb	<.001
	As	<.01
	Sn	Nil
	Ni	Nil
	Fe	<.0003
	Zn	<.02
	Cd	Nil
	Ag	<.0015
	Fe	<.01
^b 14	Bi	0.0015
	Cu	.0003
	Fe	.0003
	Ag	.00065
^c 25	Bi	0.0001
	Cu	<.0001
	Fe	.0003
	Ag	<.0001

^aSample 60 is a pig from the National Lead Co.

^bSample 14 is a single crystal grown from lead from the National Lead Co. Single crystals from this material were considered to be contaminated with bismuth. No other impurities than those given could be detected.

^cSample 24 is a single crystal grown from lead from the American Smelting and Refining Co. It was the purest lead used and most of the crystals were of that type. No other impurities than those given could be detected.



TABLE II

TEST DATA AND QUANTITIES CALCULATED FROM THEM

Specimen	Temperature (°C) (°F)	ϕ (deg)	λ (deg)	Diameter, d (mm)	τ_r, σ_r (grams/mm ²)	Increment of strain/ increment of stress at various stress levels		Steady-state creep rates at various stress levels		Total strain measured during run, ϵ_r (in./in.)	Maximum resolved shear stress to which specimen exposed, $\tau_{r,max}$ (grams/mm ²)	$\frac{\epsilon_r}{\tau_{r,max}}$	Total time of run (min)
						$\frac{\Delta \epsilon}{\Delta \tau_r}$	τ_r	$\frac{\Delta \epsilon}{\tau_r}$	$\dot{\epsilon}_r$				
bPb 2c	25	46	45	5.3	91			-0.21×10^{-4} 6.4 5.7 2.5 22.00 1.2	91 97 97 109 97	1.95×10^{-4}	109	1.42	8000
cPb 2c	25	46	45	5.3	91	1.3×10^{-4} 1.3 3.0 10.65 9.9 2.0 4.9	91 97 103 103 109 109	0.075 1.0 10.0 3.4 18.5 46.8 62.4	91 97 103 103 115 121	185	121	1.53	2890
Pb 3a	25	--	--	5.0	97	1.7	97	13.5 41.5 12 ----- ----- ----- 8.2 3.4 2.3	104 111 125 131 131 111 125 125 125	6108	131	0.82	4500
cPb 10c	25	--	--	5.0	125			11.3 2.0 0 1.8 61.25 18 120 1.9	125 125 125 125 125 131 146 131	1113	146	0.77	4700
SPb 10c	25	48	45	5.4	90	1.1	90	0.20 1.5 5.4 11.9 20.1	90 90 95 101 107 112	116	112	1.04	5000

25°C is listed when no control at room temperature was attempted.

Original run.

Remounted.

Direction perpendicular to slip plane is parallel to loosening of Tuckerman strain gage.

Time average.

Direction perpendicular to slip plane is perpendicular to loosening of Tuckerman strain gage.

Contains 0.0015 percent bismuth.



TABLE II
TEST DATA AND QUANTITIES CALCULATED FROM THEM - Continued

Specimen	Temperature (°C) (a)	ϕ (deg)	λ (deg)	Diameter, d (mm)	$\tau_{r,cr}$ (grams/mm ²)	Increment of strain/ increment of stress at various stress levels		Steady-state creep rates at various stress levels		Total strain measured during run, ϵ_r (in./in.)	Maximum resolved shear stress to which specimen exposed, $\tau_{r,max}$ (grams/mm ²)	$\frac{\epsilon_r}{\tau_{r,max}}$	Total time of run (min)
						$\frac{\Delta \epsilon}{\Delta \tau}$	τ_r	$\frac{\Delta \epsilon}{t}$	τ_r				
Pb 21a	25	53.5	37	5.8	73	0.5×10^{-4}	73	1.3×10^{-4} h 1.2 1.1 1.9 6.4 10.8	73 73 78 83 88 93 98	96×10^{-4}	100	0.96	3500
Pb 21b	25	53.5	37	5.8	73	1.4	73	0 2.3	73 73	29	73	0.40	1600
Pb N3a	-190	53	41.5	4.75	105.5	1.6 2.2 2.1 2.1 3.0 3.4 1.6 2.4 1.2 1.9	105 105 115 118 124 130 130 136.5 142.5	3.7	118	107	142	0.75	554
Pb N3b	-190	53	44	4.75	93	1.3 1.8 2.4 2.1 2.0 2.7 3.3 1.9 2.3 2.6 2.2 1.8	93 93 99 105 115 118 124 130 130 136 148			143	148	0.97	533
Pb N4b	-190	53.5	38.5	4.85	80	1.5 1.8 1.9 1.8 2.3 2.0 2.2 3.3 1.5 1.9	80 80 86 92 102 117 117 123 129	0.75 .35	92 117	122	129	0.95	1200

^a90° C is listed when no control at room temperature was attempted.

^bValue occurred after jarring when resetting scales.

^cCrystal joint gave way after 1600 min.

Note that $3.0 + 0.40 = 2 \times 1.7$.

NACA

TABLE II
TEST DATA AND QUANTITIES CALCULATED FROM THEM - Continued

Specimen	Temp- ature (°C) (°F)	ϕ (deg)	λ (deg)	Diameter d (mm)	$\tau_{T,C}$ (grams/mm ²)	Increment of strain/ at various stress levels		Steady-state creep rates at various stress levels		Total strain measured during test, ϵ_T (in./in.)	Maximum resolved shear stress to which specimen exposed, $\tau_{T,max}$ (grams/mm ²)	$\frac{\epsilon_T}{\tau_{T,max}}$	Total time of run (min)
						$\frac{\Delta\epsilon}{\Delta\tau}$	τ_T	$\frac{\Delta\epsilon}{\Delta t}$	τ_T				
Pb H5a	28	46.5	43.5	4.8	94.5	0.15×10^{-4} 81 88 94.5	81 88 94.5	0.6×10^{-4} 2.2 23	81 88 94.5	28×10^{-4}	94.5		260
Pb H5b	-190	47	48	4.8	94.5	0.6 4.8 6.4 6.2 7.7	94.5 102 102 108 108	0.5 1.7	102 108	108	108	1.0	690
TiCu 2A1	25	56	34	5.45	356					5.7	356	0.016	160
TiCu 2A2	25	56	34	5.45	356					4.5	366	0.012	190
Cu 2D	25	50	40	5.45	173	0.48 1.0 1.6 2.0 2.16 2.16 2.30 2.44 2.59 2.86 3.02 3.16 3.74	173 187 202 202 216 216 230 244 259 286 302 316 374	0.01	259	121	374	0.32	6600
Cu 5B2	25	39	53.5	5.4	217	0.60 1.45	217 225			43	225	0.2	245
Cu 9B1	25	55	35	5.4	280	0.29 0.29 0.36 0.47	280 308 335 374	0.12 0.33 0.45	280 308 374	54	374	0.14	2800
Cu 9B2	25	55	35	5.4	224	0.25 0.53 0.53 0.63 0.32 0.54	224 228 280 308 335 363 374	0.11 0.07	308 374	95	374	0.25	2250

Temp C is listed when no control at room temperature was attempted.

Double spots on X-ray picture.

Hydrous-annealed.

Hydrogen-annealed.

Crystal joint broke after 45 min.



TABLE II

TEST DATA AND QUANTITIES CALCULATED FROM THEM - Concluded

Specimen	Temperature (°C) (°F)	ϕ (deg)	λ (deg)	Diameter, d (mm)	$\tau_{r,cr}$ (grams/mm ²)	Increment of strain/ increment of stress at various stress levels		Steady-state creep rates at various stress levels		Total strain measured during run, ϵ_T (in./in.)	Maximum resolved shear stress to which specimen exposed, $\tau_{r,max}$ (grams/mm ²)	$\frac{\epsilon_T}{\tau_{r,max}}$	Total time of run (min)
						$\frac{\Delta\epsilon}{\Delta\tau_r}$	τ_r	$\frac{\Delta\epsilon}{t}$	τ_r				
Cu 11B2	25	47.5	43.5	5.4	318	2.1×10^{-4}	318	0.16×10^{-4}	338	175×10^{-4}	344	0.51	2750
						3.8	332						
						3.4	338						
						3.4	344						
						6.0	344						
Zn XI	25	68	24	5.5	39 23.4	1.7	23.4	15	27.3	78	31.2	0.25	940
						1.5	27.3	300	31.2				
Zn XIV	25	72	25	5.6	33	1.0	33	15	33	57	36	1.58	1060
						2.2	33	49	36				
						4.2	36						

^a25° C was listed when no control at room temperature was attempted.

^oInadvertently loaded to approx. 39 grams/mm² at first.



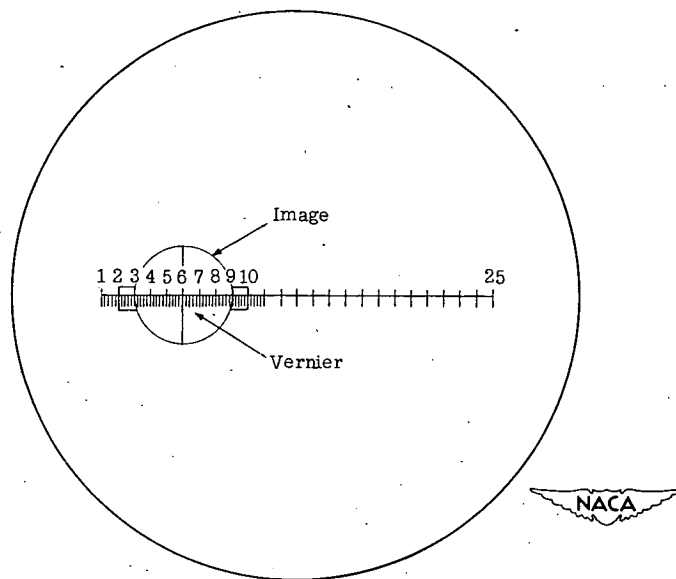


Figure 2.- View into autocollimator.

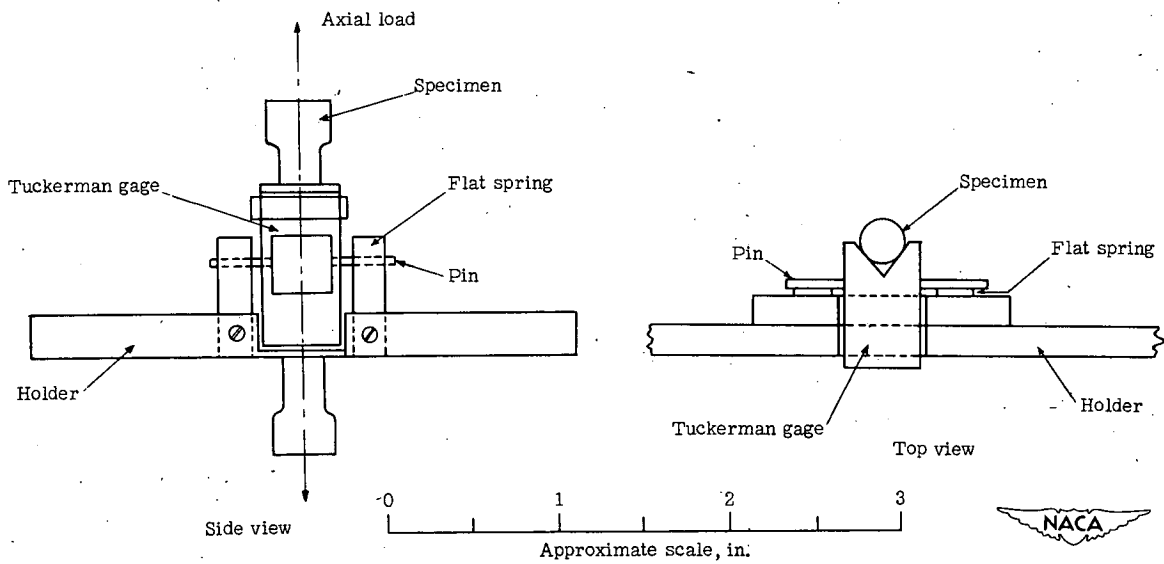


Figure 3.- Top and side views of gage holders. Compare figure 1.

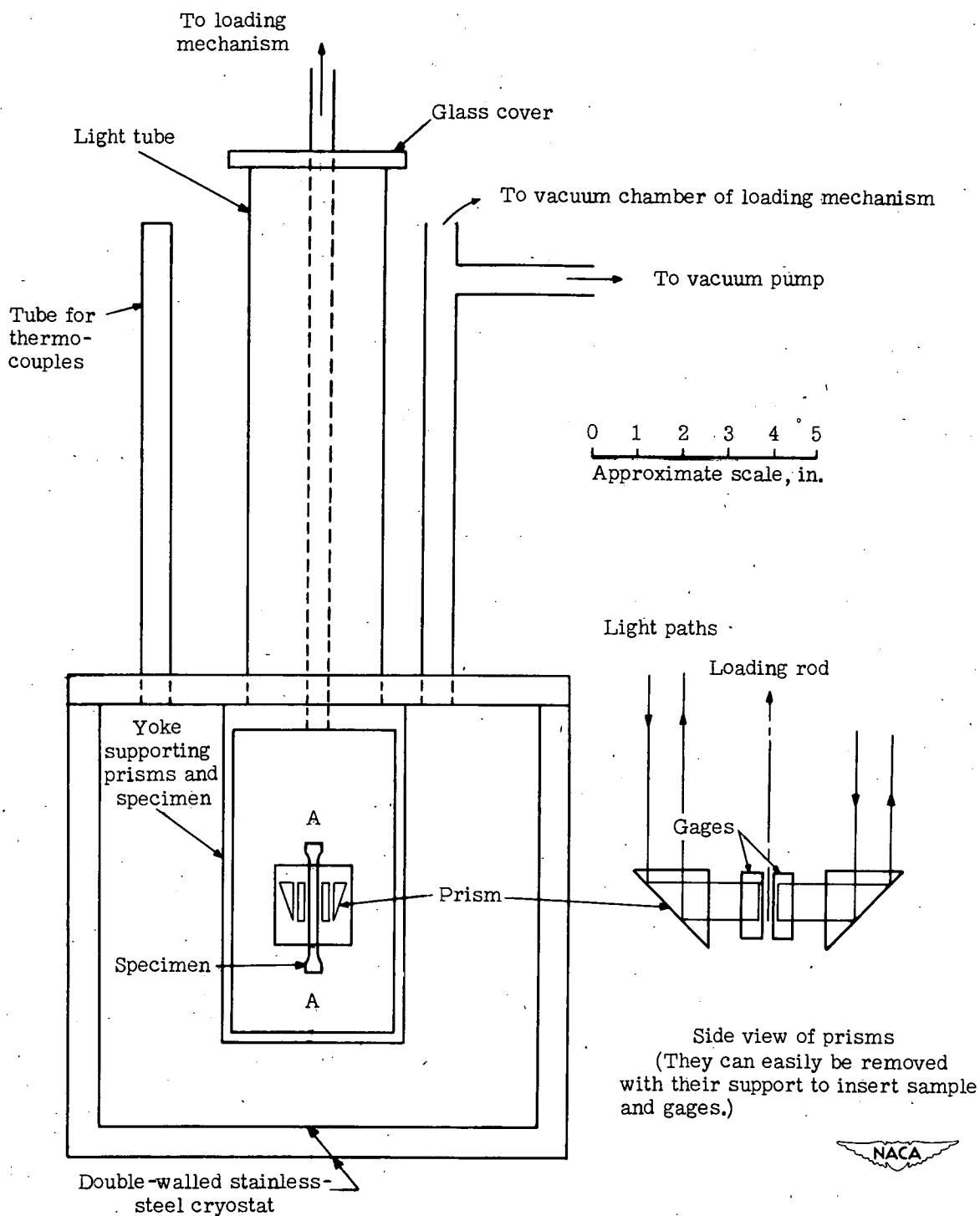


Figure 4.- Over-all view of gages and specimen in cryostat. Supporting tubes of cryostat cover and flexible joints and specimen grips at A are not shown.

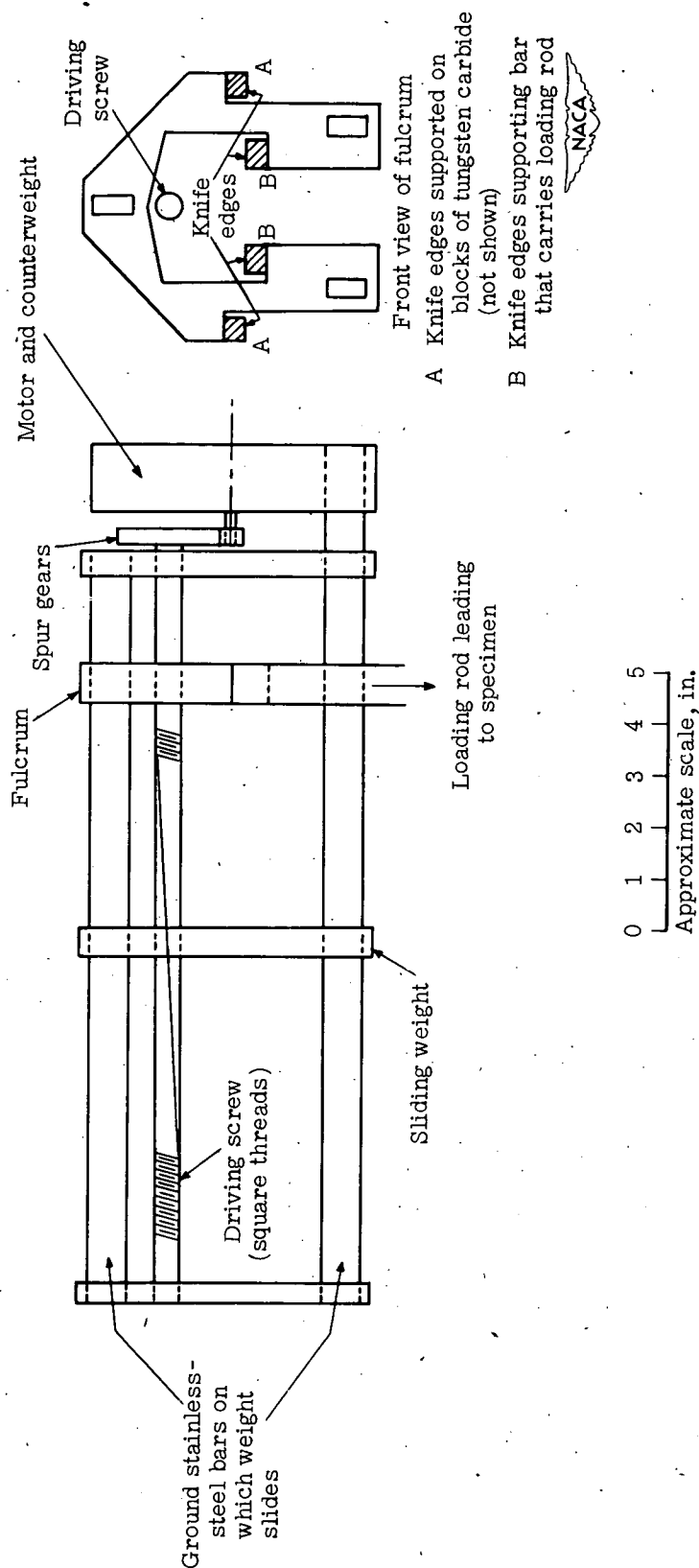


Figure 5.- Over-all view of loading device. The cover, a rectangular box with a glass window, and scale are not shown.

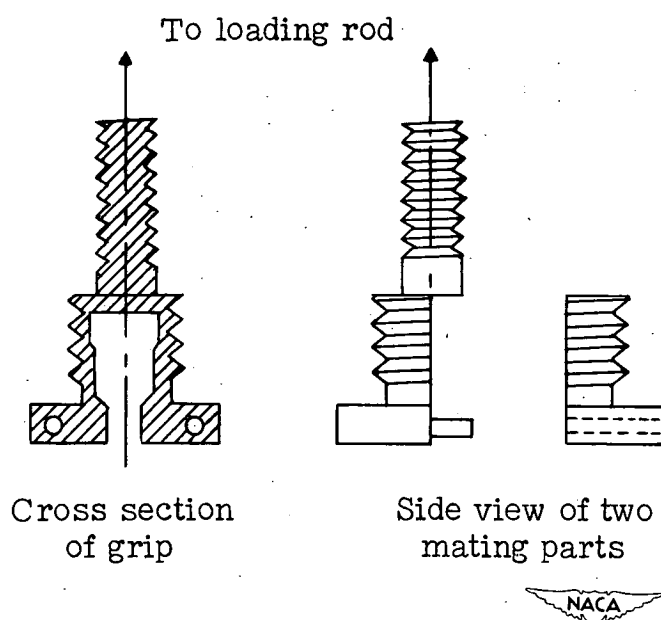


Figure 6.- Specimen grips. Nut holding two parts together is not shown.
Full scale.

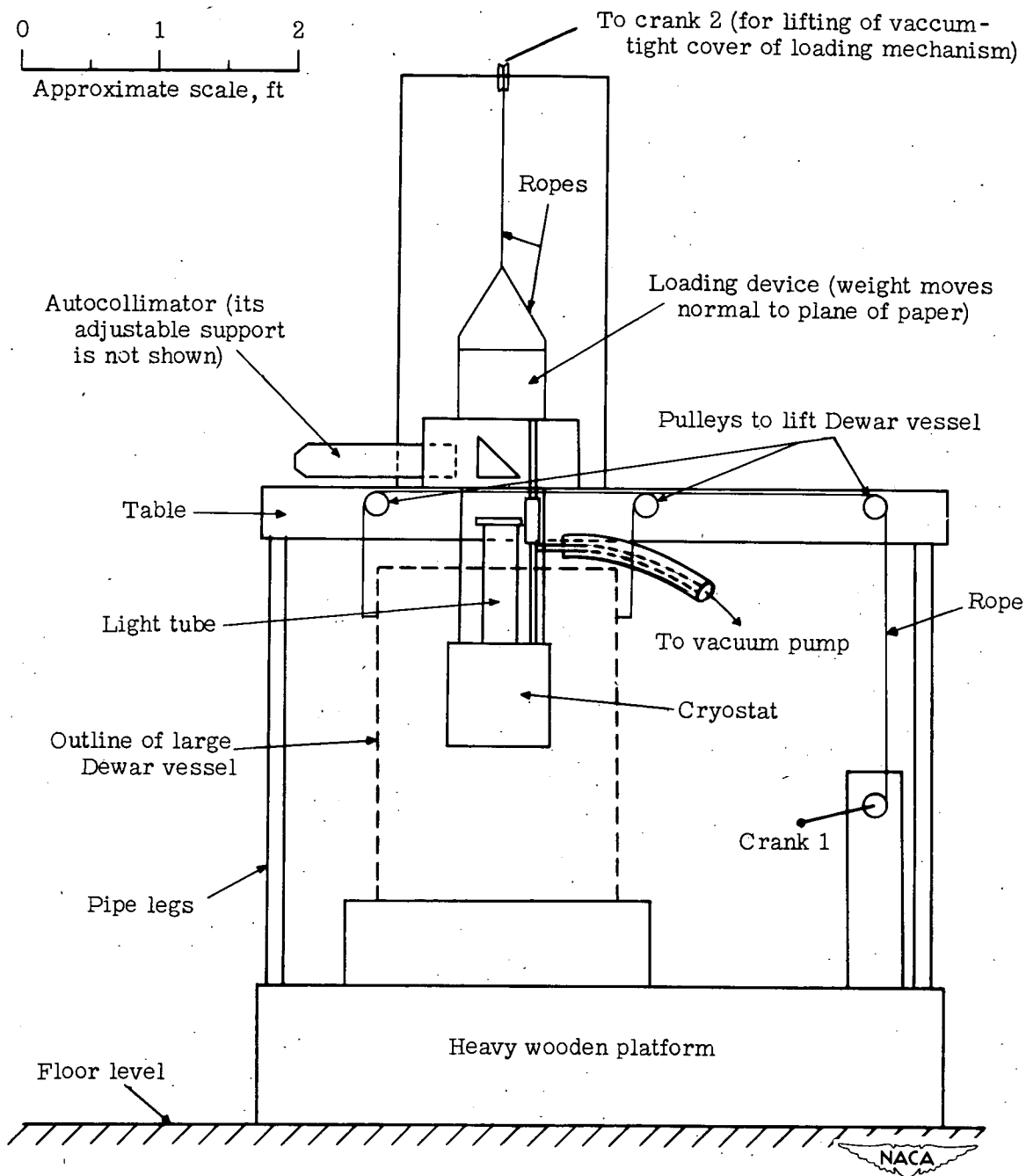


Figure 7.- Over-all view of creep apparatus. Accessory equipment not shown.

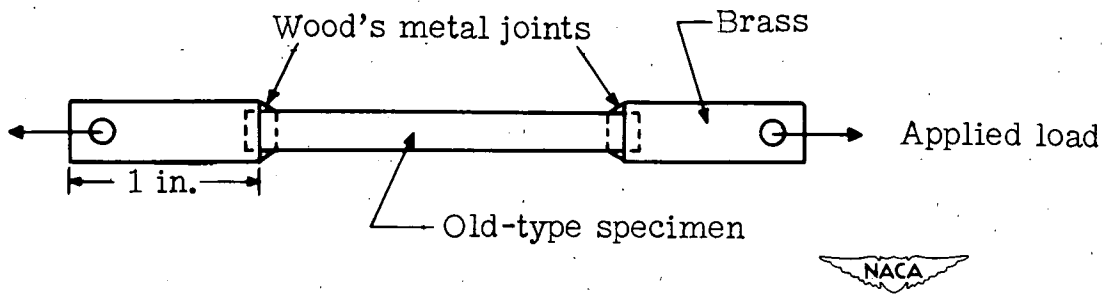


Figure 8.- Mounted old-type specimen.

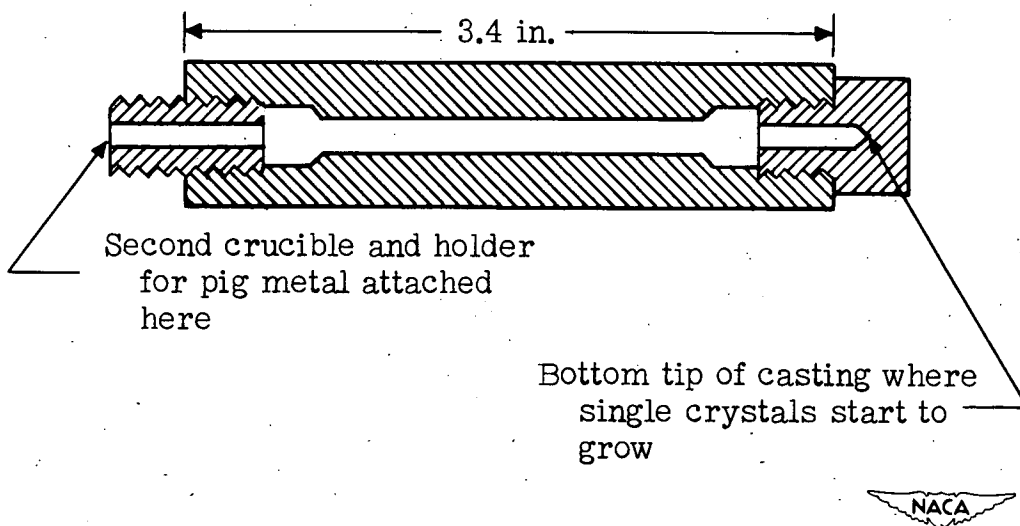
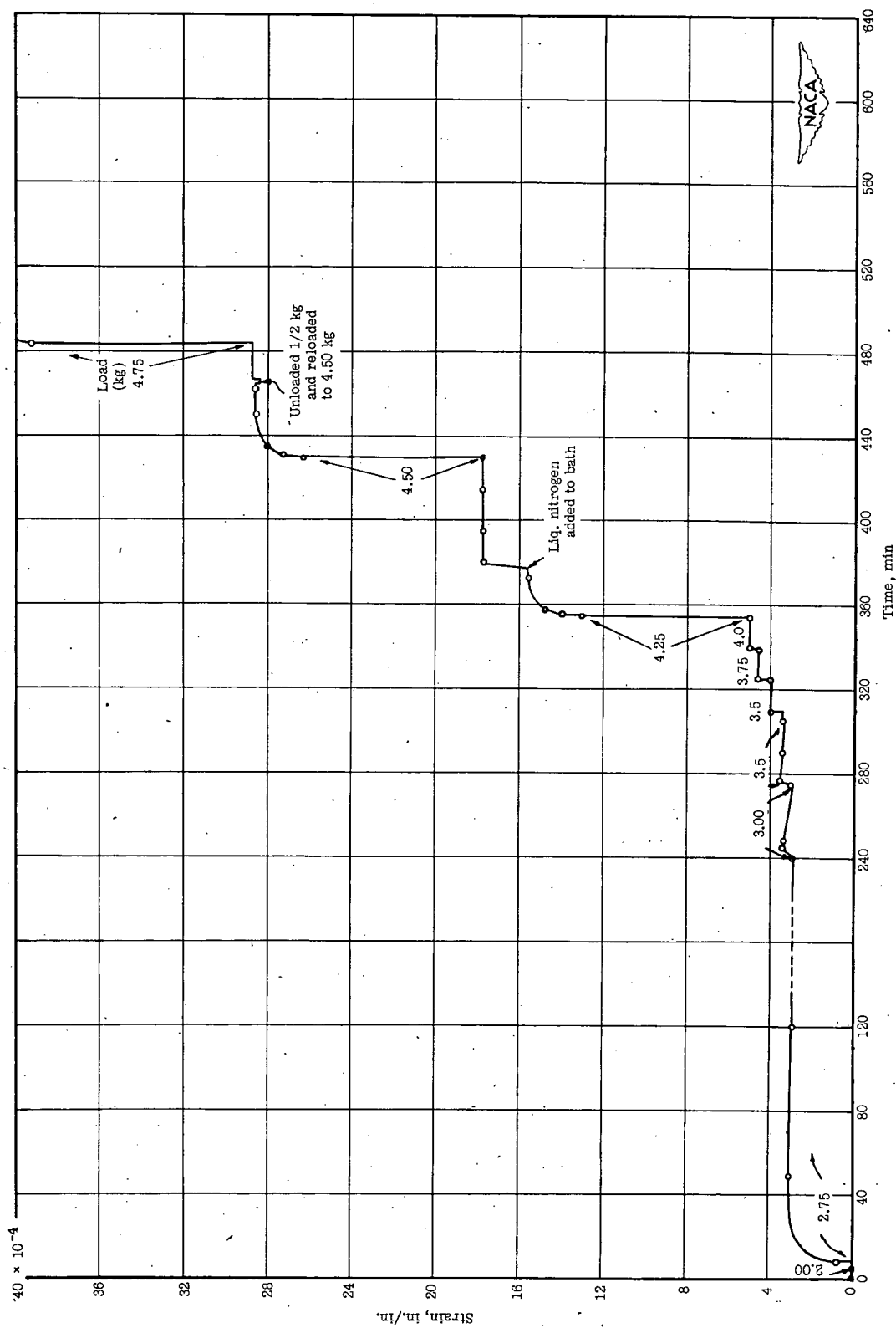
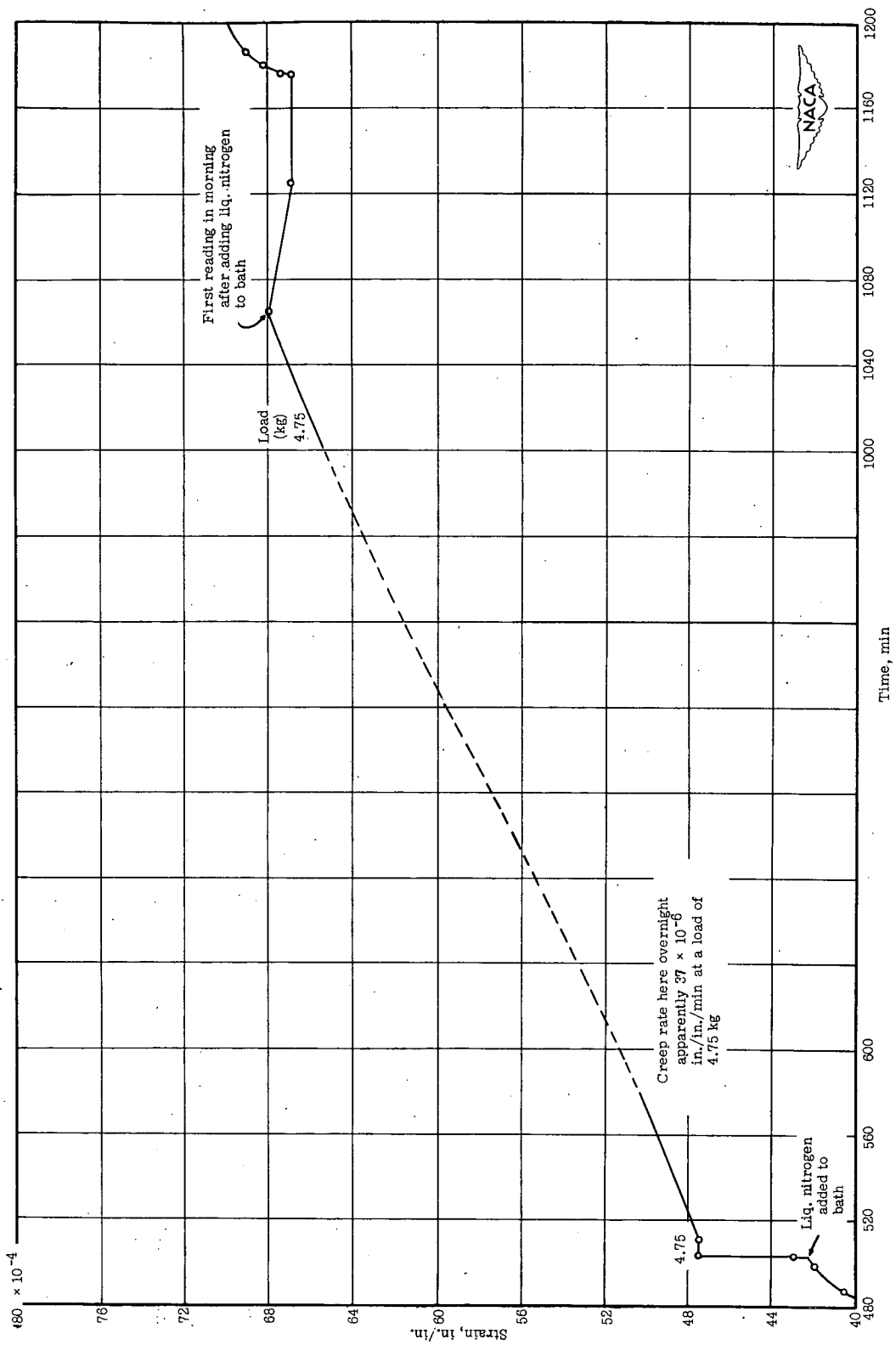


Figure 9.- Cross-sectional view of graphite crucible for new-type specimen.



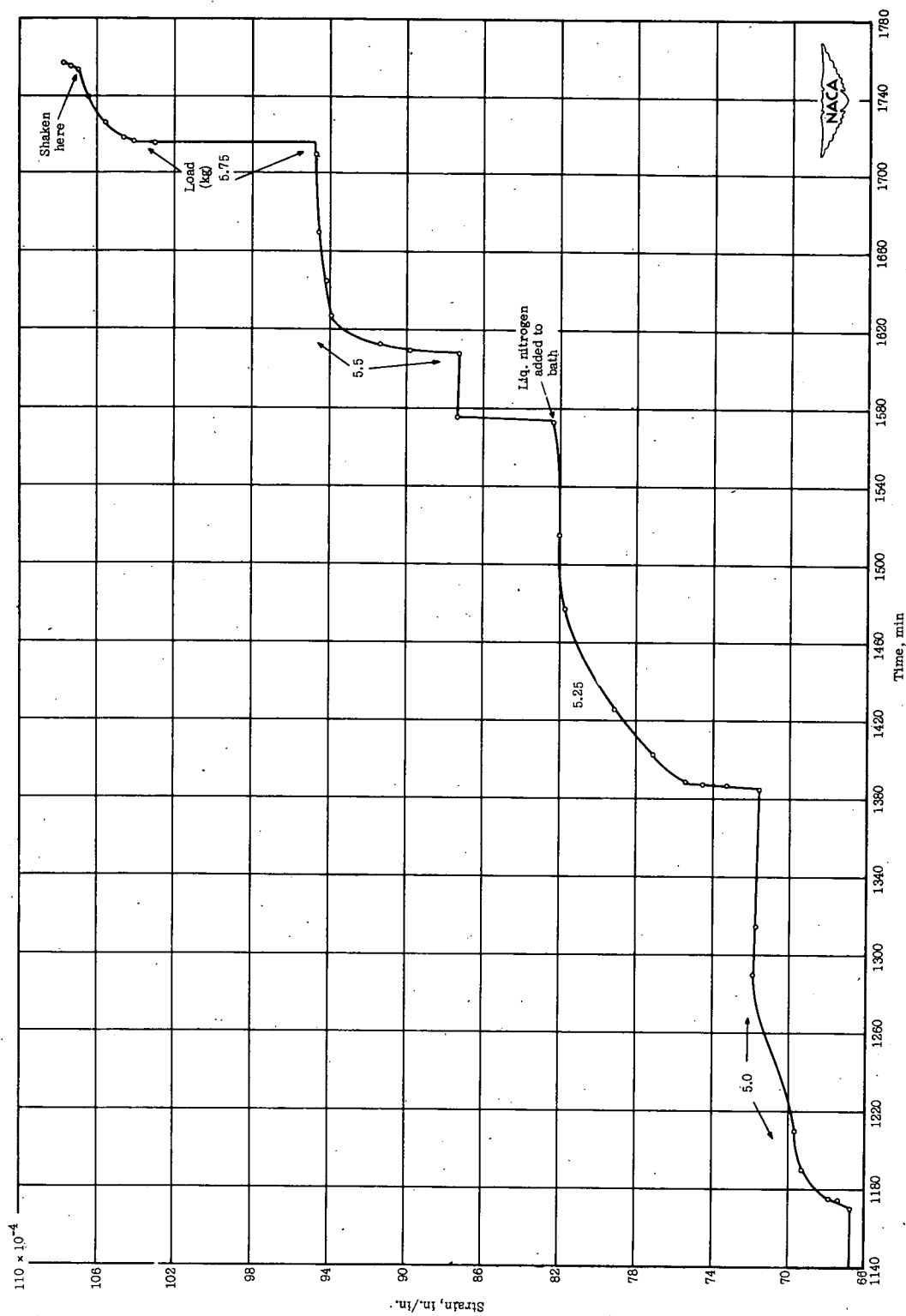
(a) Strain range from 0 to 40×10^{-4} inch per inch; time range from 0 to about 480 minutes.

Figure 10.- Creep test on lead crystal N3a at about -190°C .



(b) Strain range from 40×10^{-4} to about 70×10^{-4} inch per inch; time range from 480 to 1200 minutes.

Figure 10.- Continued.



(c) Strain range from about 67×10^{-4} to about 108×10^{-4} inch per inch; time range from 1140 to about 1760 minutes.

Figure 10.- Concluded.

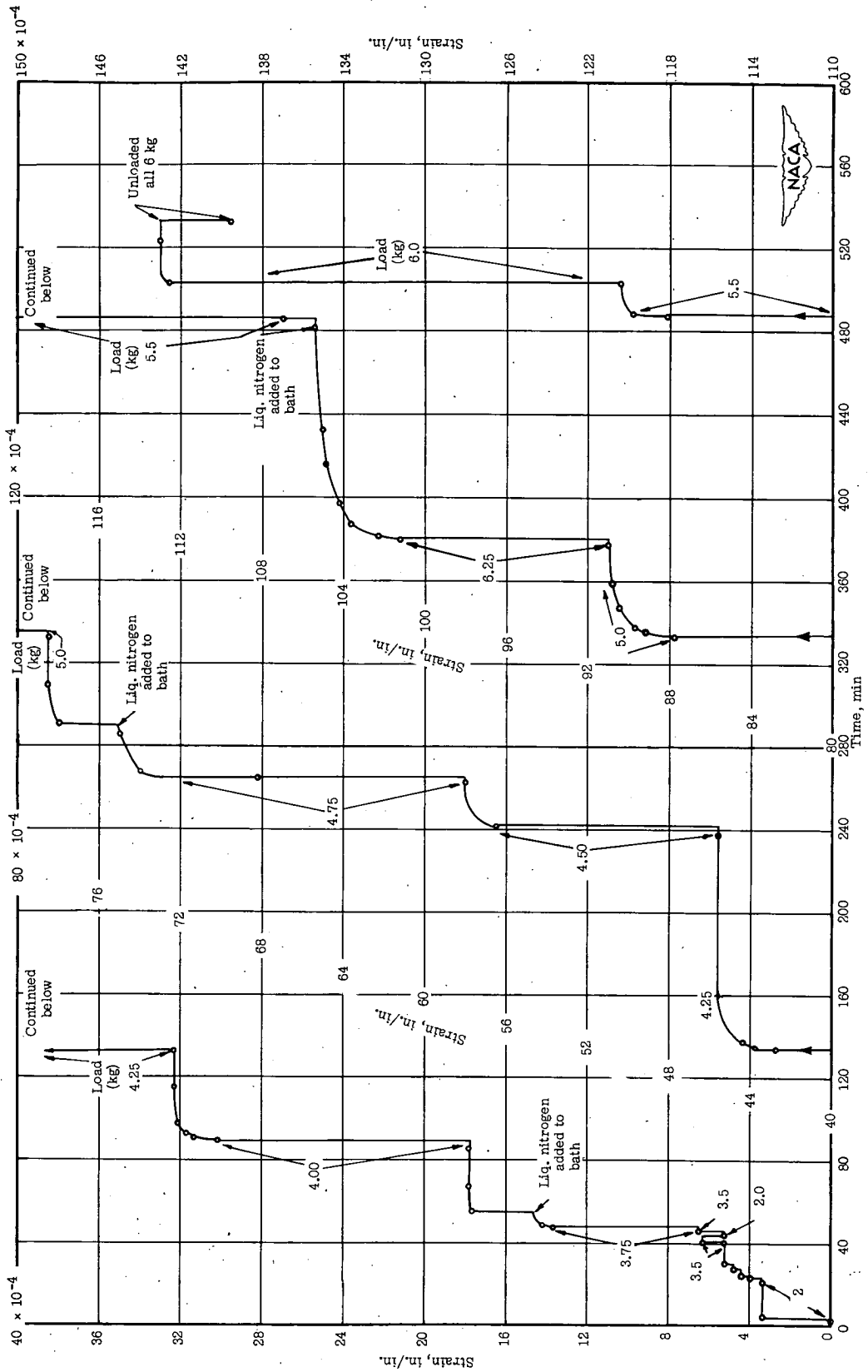


Figure 11.- Creep test on lead crystal N3b at about -190° C.

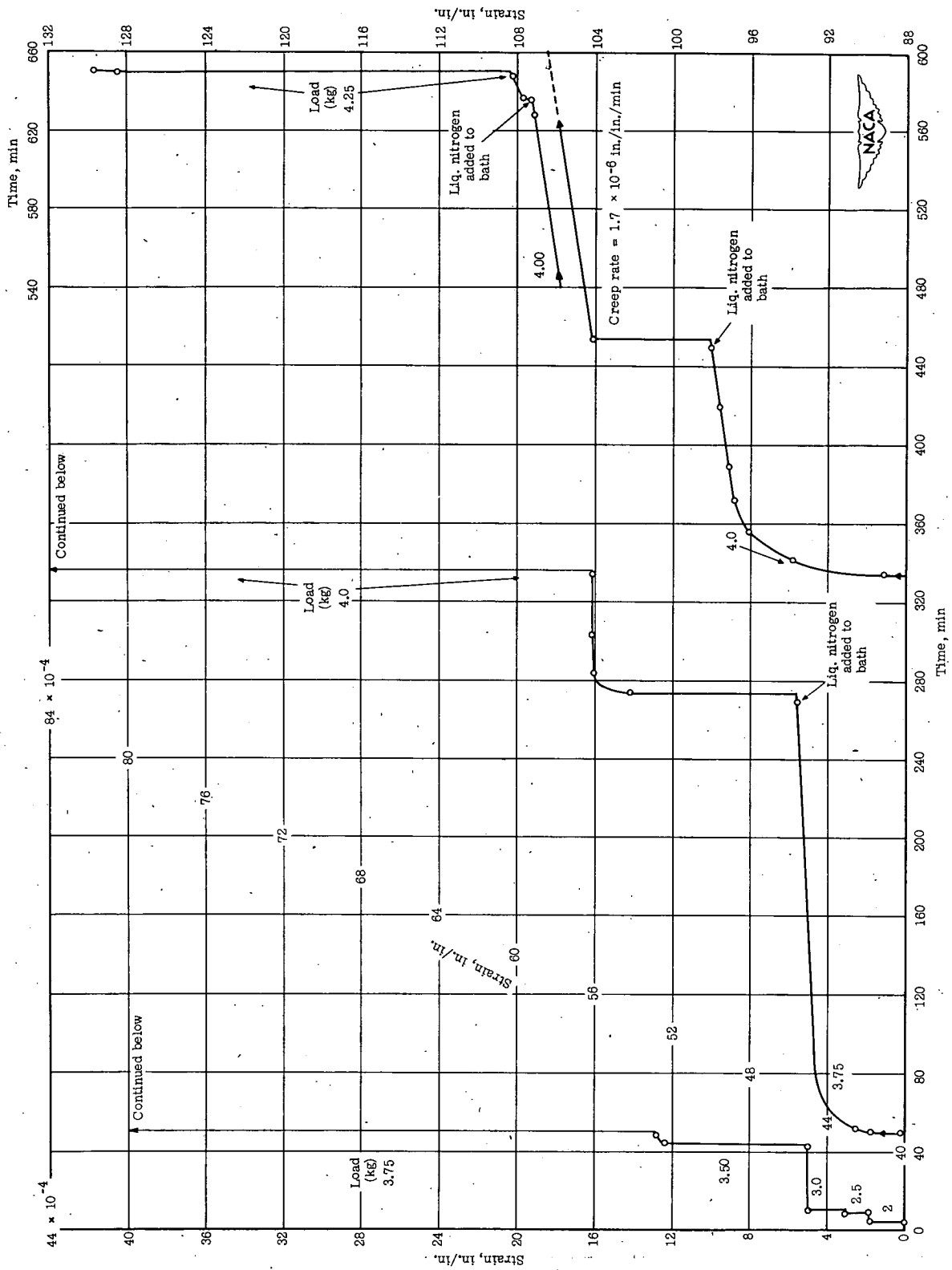


Figure 12.- Creep test on lead crystal N5b at about -190°C . Scale at top goes with upper curve on right.

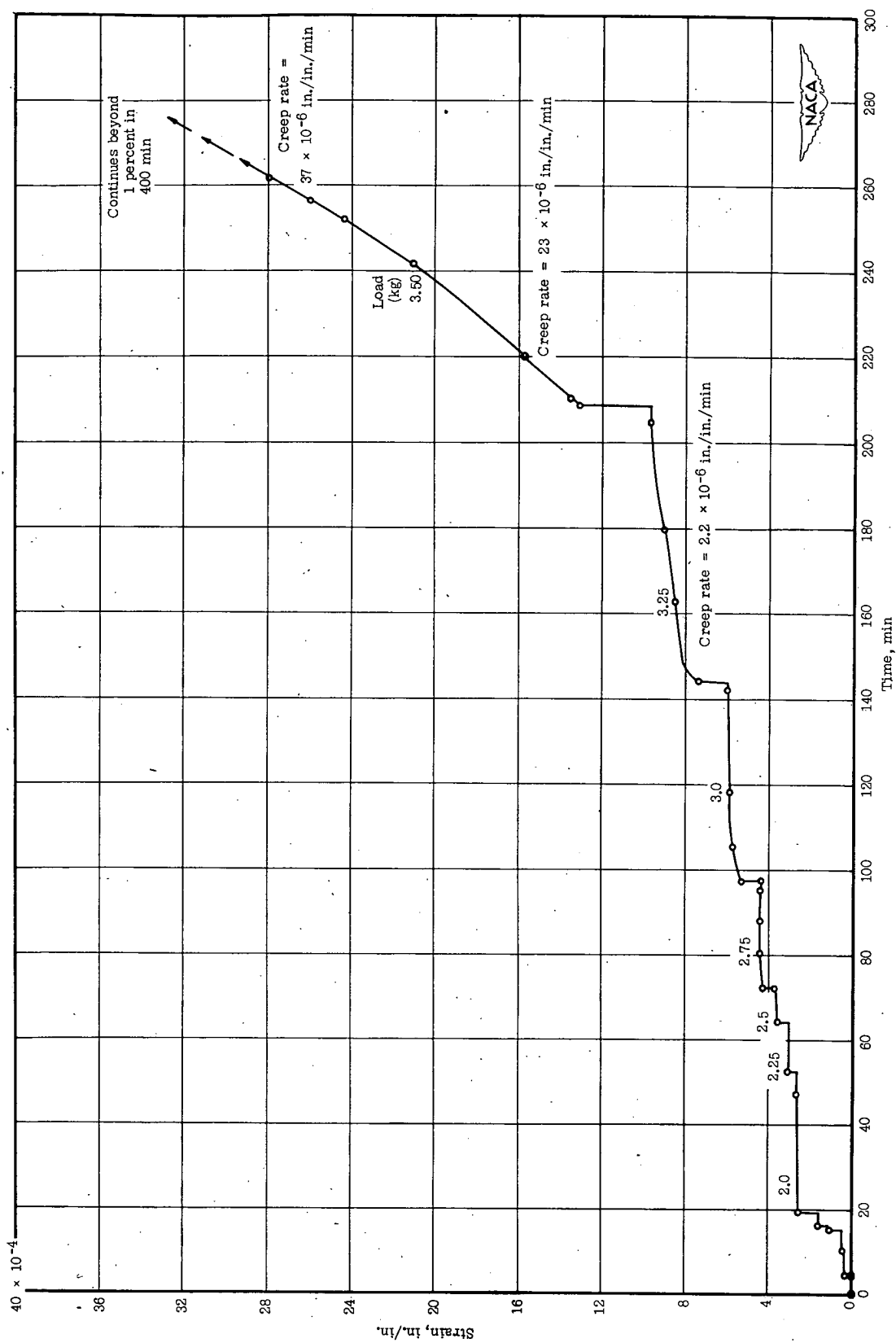


Figure 13.- Creep test on lead crystal N5a at about 28° C.

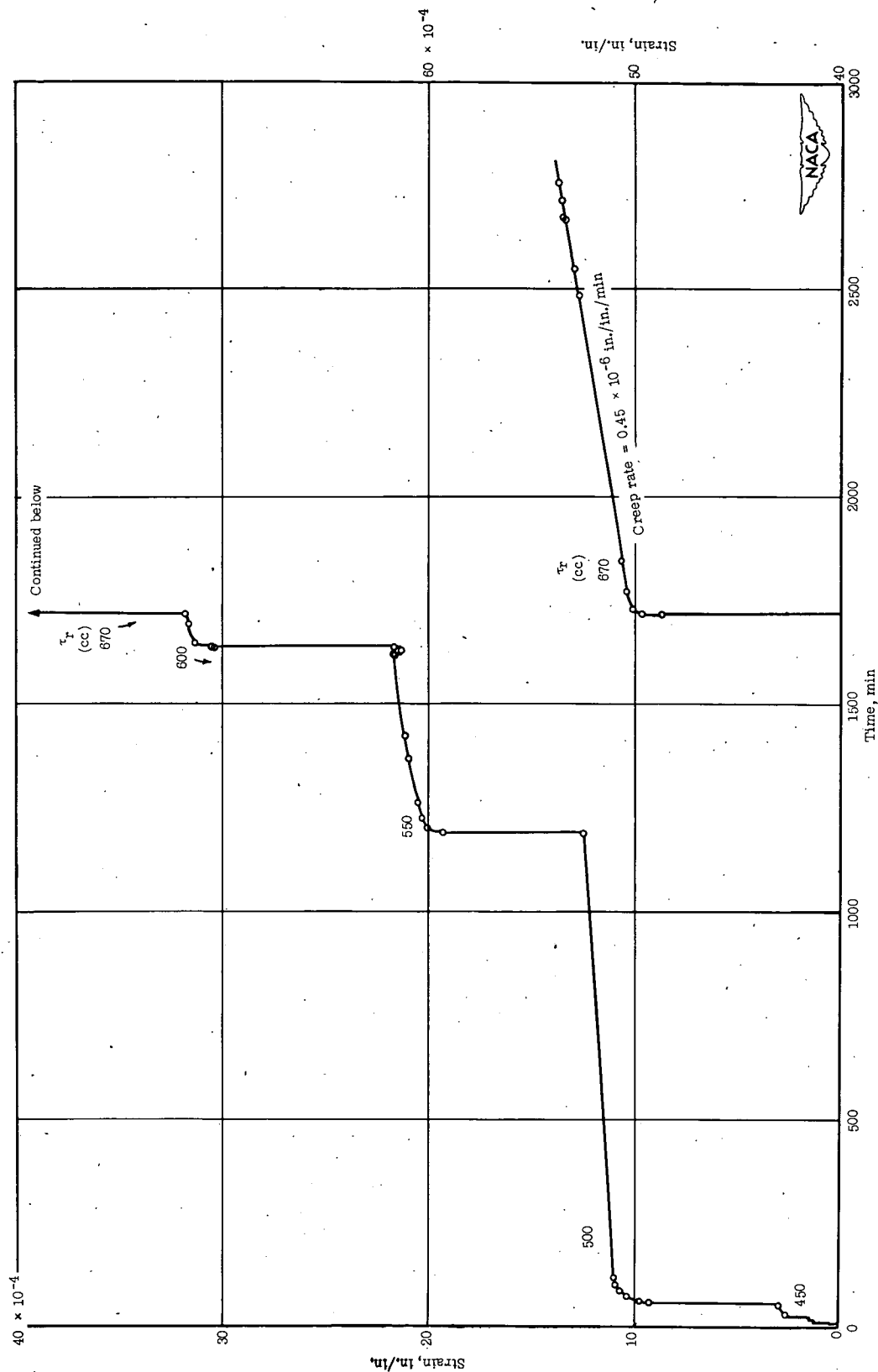
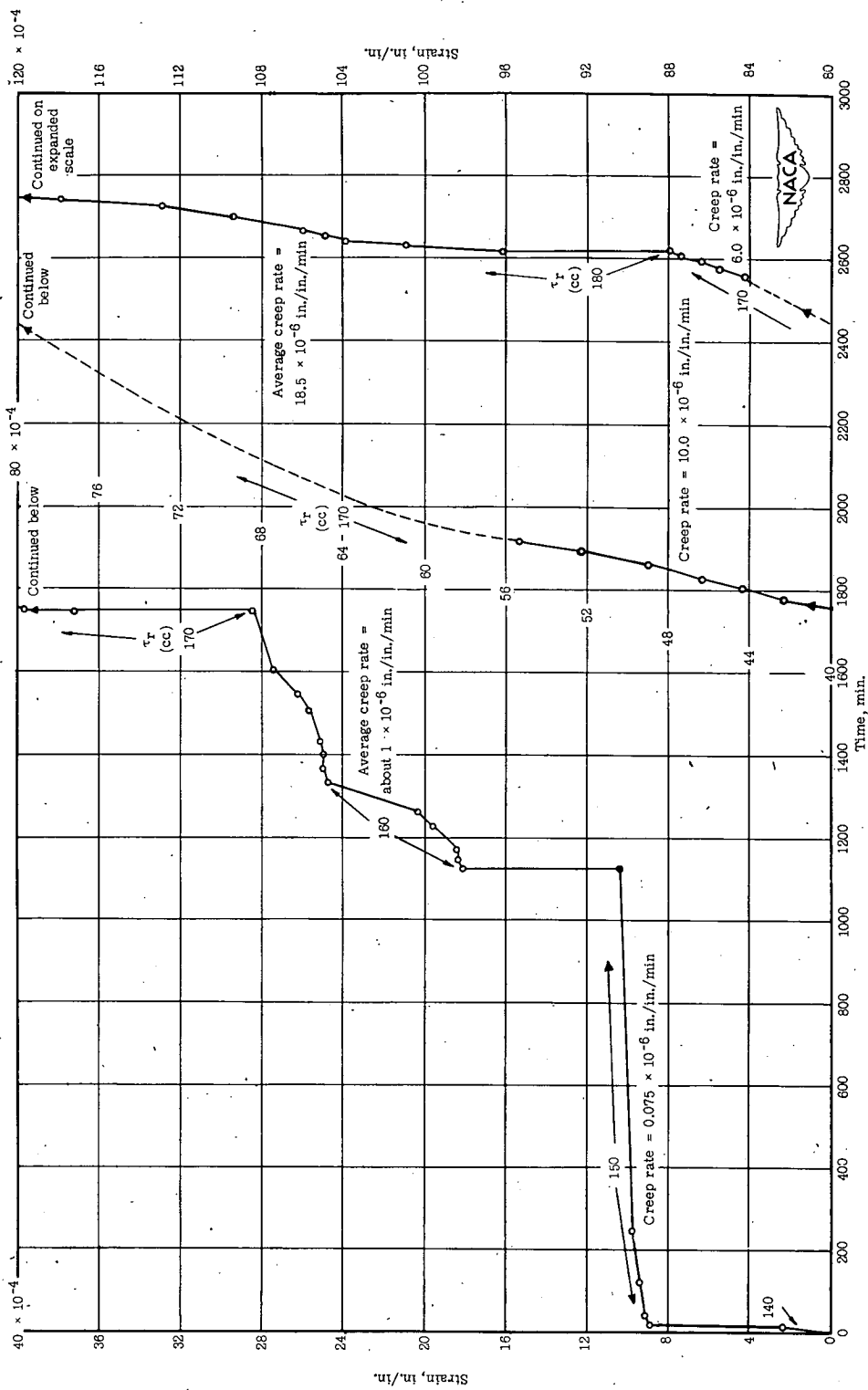
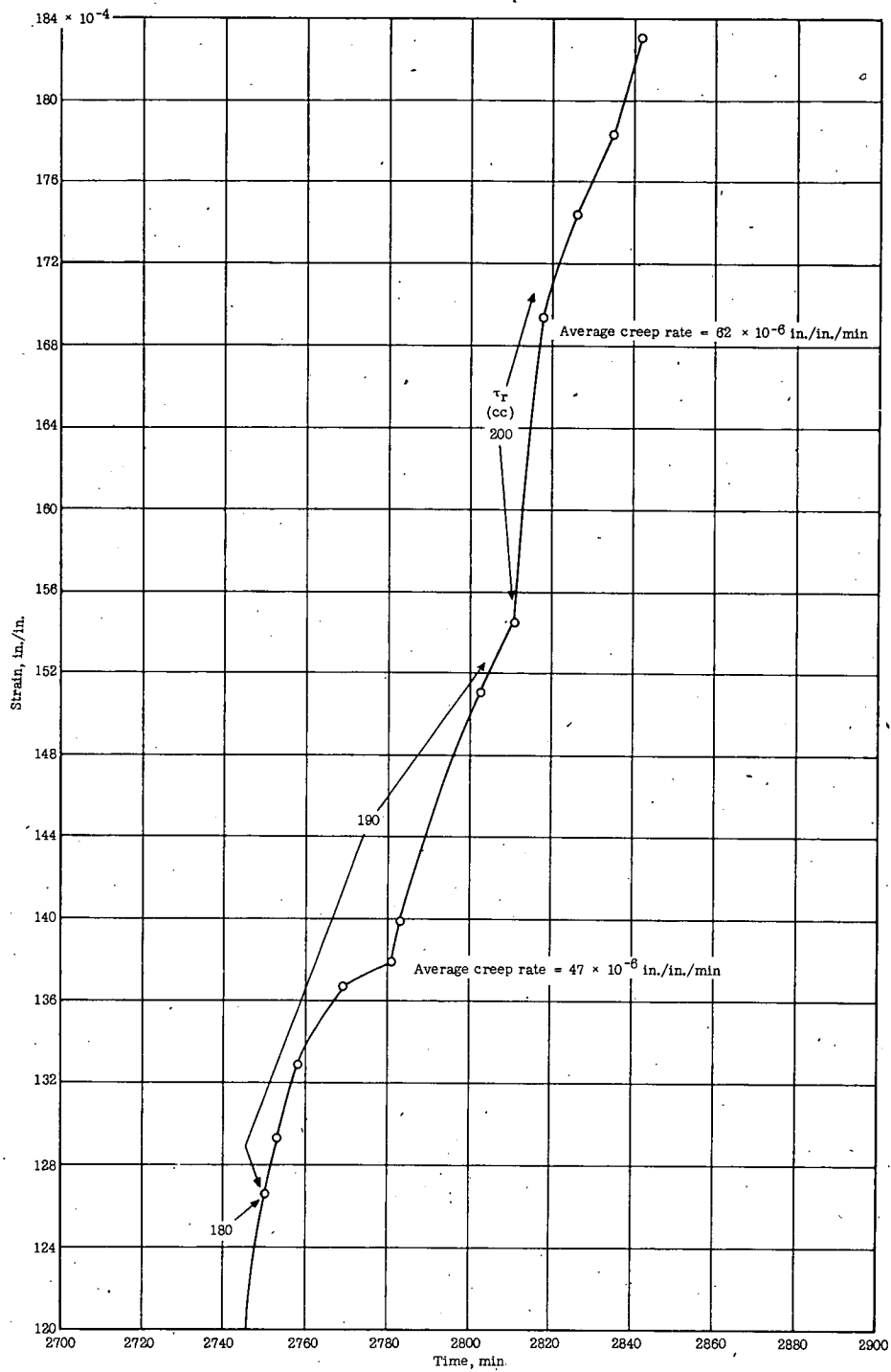


Figure 14.- Creep test on copper specimen 9B-1 at about 25° C; 100 cubic centimeters equals 56 grams per square millimeter of resolved shear stress. Right-hand scale goes with curve at right.



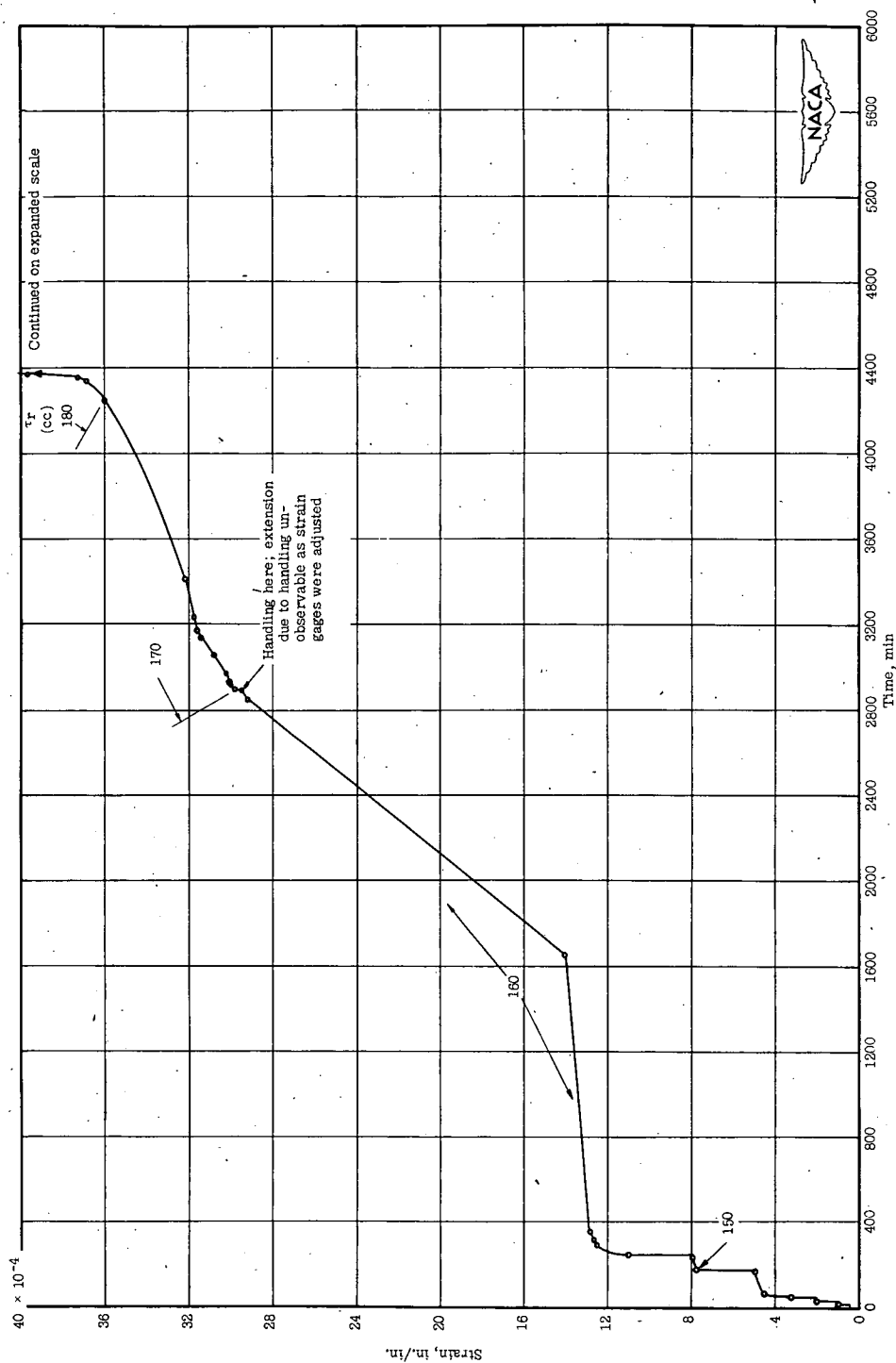
(a) Strain range from 0 to 120×10^{-4} inch per inch; time range from 0 to about 2750 minutes.

Figure 15.- Creep test on lead crystal 2C at about 25°C ; 100 cubic centimeters approximately equals 61 grams per square millimeter of resolved shear stress.



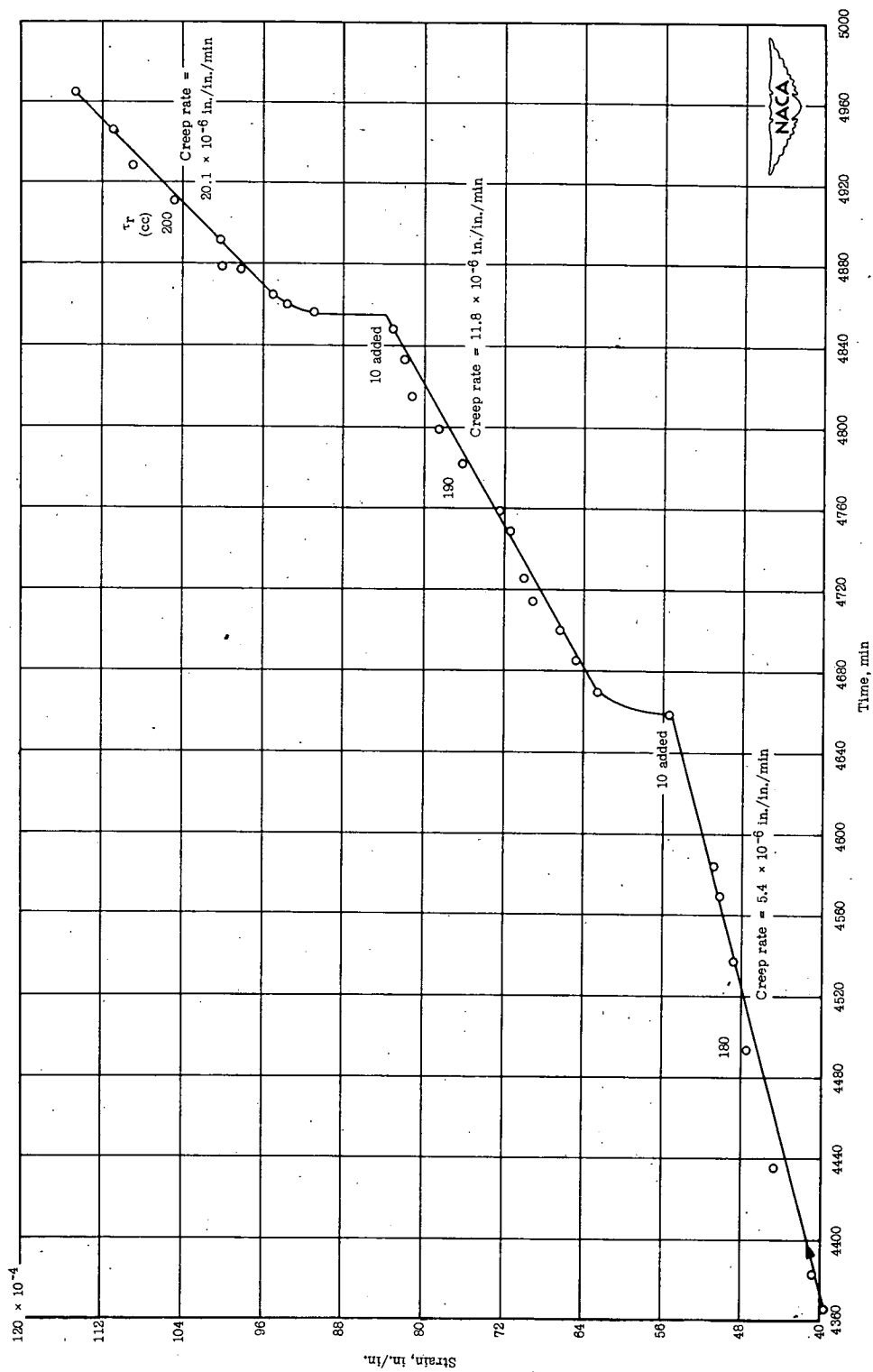
(b) Expanded scale with strain range from 120×10^{-4} to about 184×10^{-4} inch per inch; time range from about 2745 to about 2840 minutes.

Figure 15.- Concluded.



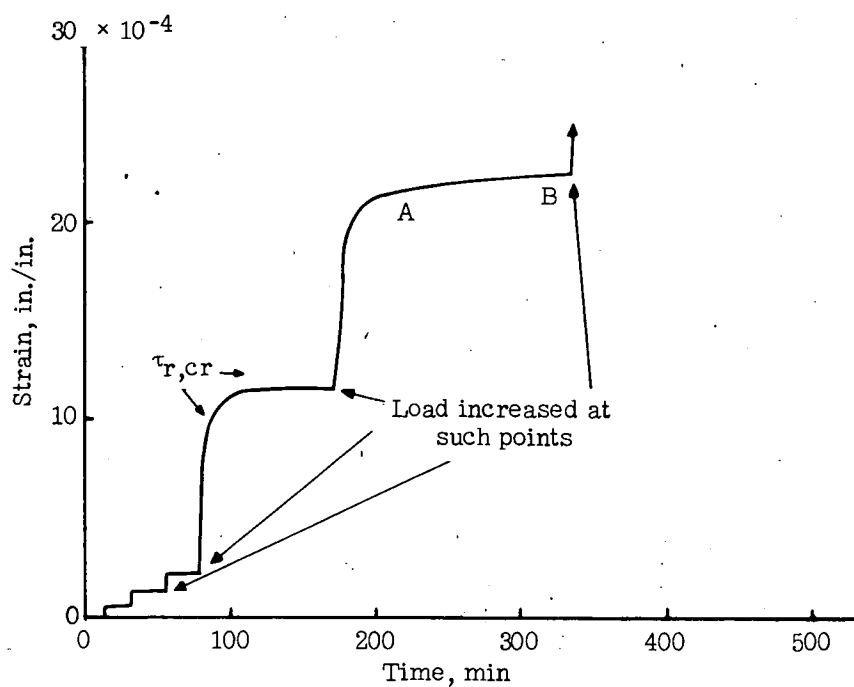
(a) Strain range from 0 to 40×10^{-4} inch per inch; time range from 0 to about 4400 minutes.

Figure 16.- Creep test on lead crystal $10C$ at $25^{\circ}C$; 100 cubic centimeters equals 56 grams per square millimeter of resolved shear stress.



(b) Expanded scale with strain range from about 40×10^{-4} to about 115×10^{-4} inch per inch; time range from about 4360 to about 4970 minutes.

Figure 16.- Concluded.



(a) Transient creep.

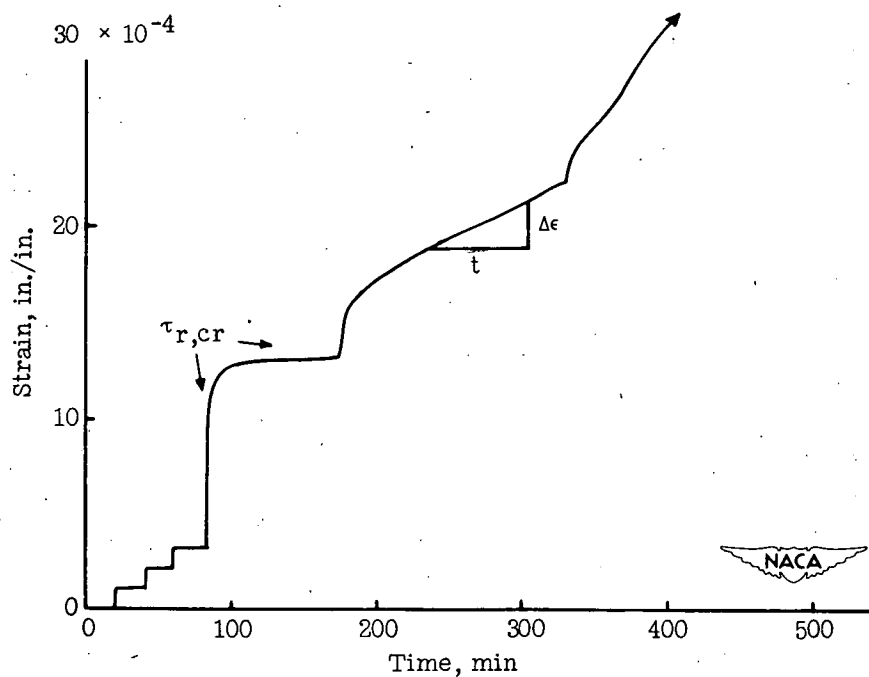
(b) Steady-state creep. Steady-state creep rate is $\Delta\epsilon/t$.

Figure 17.- Typical stress-strain-time curves showing various types of creep.